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Thermal processing of fresh concrete with infrared radiation

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Abstract. Currently, the construction of buildings made of monolithic concrete and reinforced concrete is becoming increasingly relevant. The use of innovative technologies, minimum construction time, durability, reliability, the ability to perform work in various climatic conditions, architectural individuality contribute to the development of monolithic construction. Concrete and reinforced concrete are the main materials of modern construction. The quality of structures depends not only on the composition of concrete, the amount of portland cement, the chemical additives used, the water-cement ratio, the quality of fillers, etc., but also significantly on the heat and humidity regime of concrete holding. To ensure the necessary temperature conditions for hardening and strength gain of concrete, various methods of heating structures are used. One of the methods of concrete care is thermal processing during the hardening period and the acquisition of critical or design strength. The aim of the study is to improve the technology of erection of monolithic concrete and reinforced concrete structures using thermal processing of concrete by means of infrared radiation. The technology of thermal processing of the laid and compacted concrete mixture using infrared heating and a two-chamber transparent shelter for infrared rays has been developed. The obtained results permit us to provide conditions for the normal course of the chemical reaction of hydration, hardening and strength gain. This allows successfully solve the problems of concreting in the erection of buildings and structures made of monolithic concrete and reinforced concrete.

Keywords: concrete, temperature, heating, infrared radiation, monolithic reinforced concrete structures

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Термическая обработка свежего бетона инфракрасным излучением

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Аннотация. В настоящее время все большую актуальность приобретает строительство зданий из монолитного бетона и железобетона. Применение инновационных технологий, минимальные сроки строительства, долговечность, надежность, возможность выполнения работ в различных климатических условиях, архитектурная индивидуальность способствуют развитию монолитного строительства. Бетон и железобетон являются основными материалами современного строительства. Качество конструкций зависит не только от состава бетона, количества портландцемента, применяемых химических добавок, водоцементного отношения, качества наполнителей и др., но и существенным образом от тепловлажностного режима выдерживания бетона. Для обеспечения необходимых температурных условий твердения и набора прочности бетона используют различные методы прогрева конструкций. Одним из них является тепловая обработка в период твердения и приобретения критической или проектной прочности. Цель исследования – совершенствование технологии возведения монолитных бетонных и железобетонных конструкций с использованием тепловой обработки бетона посредством инфракрасного излучения. Разработана технология тепловой обработки уложенной и уплотненной бетонной смеси с использованием инфракрасного обогрева и двухкамерного прозрачного для инфракрасных лучей укрытия. Полученные результаты обеспечивают условия для нормального протекания химической реакции гидратации, твердения и набора прочности, что позволяет успешно решать задачи бетонирования при возведении зданий и сооружений из монолитного бетона и железобетона.

Ключевые слова: бетон, температура, обогрев, инфракрасное излучение, монолитные железобетонные конструкции

Introduction

Monolithic construction is one of the most promising technologies used in the construction of various buildings and structures. The emergence of a wide range of new materials and the development of innovative construction technologies significantly simplify the process of building structures, making it more economical and faster. One of the methods of concreting is the thermal processing of a monolithic structure during its hardening and the acquisition of critical or design strength. For the production of works with the thermal processing of concrete, several technical solutions and methods of their implementation are used with varying degrees of adaptation to the peculiarities of concreting technology. Technological, chemical and thermal methods are used to provide conditions for accelerating the hardening of concrete. The most effective methods of accelerating the hardening of concrete are thermal methods. In the practice of construction, the most widely used methods of concreting are: "thermos," preliminary electric heating of the concrete mixture, electric heating, heating in the heating formwork, induction heating, concreting in "greenhouses," steam heating, heat treatment in solar installations, heat treatment with radio waves, etc.

Concrete maintenance is necessary both in hot, dry weather and in winter. Curing of concrete in a hot, dry climate is difficult due to the limited availability of water for curing and (or) rapid loss of moisture as result of

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evaporation. It has been established that self-curing chemical additives (water-soluble polyethylene glycol (PEG 400)) are effective in improving the physical properties of concrete, such as water retention, water absorption and permeability [1]. The practice of construction in hot climates has established that in the absence of care for freshly laid concrete during the first day alone, concrete by the age of 28 days gains on average only about 86% of R_{28}, in the absence of care during the first two days – about 77%, within five days – about 74%. Concrete that has hardened in the sun without care, by 28 days, gains no more than 50–55% of the strength at 28 days of age. It is established that in the conditions of a sharply continental climate, due to cyclic heating during the day to 70 °C and cooling at night to 15 °C and below, there is a shortage of the strength of concrete with an open surface. Concrete of such a construction and at the age of 28 days can have a strength of only about 50% of the design strength (R_{28}) [1–3].

Without special technological measures to regulate the temperature of the concrete mass, it is impossible to ensure the holding mode of the concrete mixture laid in the structure, allowing it to gain critical strength [4; 5]. The paper [6] describes the heat treatment of concrete at the early stages of hydration using radio wave technology.

The state of its moisture content depends on the conditions of concrete holding, which plays a significant role in the structure formation of concrete. The regularities of changes in the moisture content of concrete during heat treatment and its effect on the kinetics of concrete strength growth at an early age (1–3 days) and on subsequent hardening periods have been studied [7]. It is shown that there is a critical value of concrete moisture and a decrease in its less critical value leads to a suspension of the cement hydration process and to irreversible processes.

Uncontrolled heating rate or excessively high maximum temperatures lead to unfavorable heat treatment of fresh or young concrete locally or throughout the concreted surface. In addition to affecting the morphology, an increase in temperature during the hydration process affects the chemical processes of hardening concrete. Portland cement is a complex system that consists of four main clinker minerals. The product of the interaction of cement with water is a solidified cement paste with a single structure, however, clinker minerals interact with the mixing water almost independently of each other, and the hydration activity of minerals decreases in the series C_3A, C_4AF, C_3S, C_2S. When studying the mechanism of hydration of portland cement, the influence of all minerals is taken into account. Considering the process of hydration of portland cement, the influence of C_3A should not be underestimated. Aluminate is the most reactive mineral and instantly interacts with water with significant heat release, which causes rapid setting. As result of improper thermal curing, the formation of calcium hydrosulfoaluminate is possible, which can lead to cracking of the surface and serious damage to the concrete structure. Under normal conditions, cement paste and concrete mixtures can retain their technological properties for a certain time. However, there are factors that can change the rate of cement hydration: ambient temperature, relative humidity, wind speed, specific surface area of the structure, chemical and mineralogical composition of portland cement, physical and mechanical properties of portland cement, additives, improper heat treatment, etc. [8–12]. Monitoring and maintaining the temperature regime of hydration allows you to prevent negative phenomena in hardening concrete and significantly improve the quality of concrete.

The subject of the study [3] is to determine the influence of humidity on the development of mechanical properties of portland cement mortars under various curing modes. It is determined that the well-known maturity formula, which is a function of the time interval and temperature, is not applicable for a climate with a relative humidity below 75%. In such climatic conditions, the compressive strength decreases by up to 40% and the bending strength decreases by up to 30% compared to standard curing.

An experimental study on the prediction of early-age thermal cracks in massive concrete structures in the tropics is presented [13]. The development of cracks will affect the ability of the concrete structure to withstand the design load and will further destroy its integrity and durability [14; 15]. Methods of controlling the maximum temperature and preventing the formation of cracks in concrete are considered [16–18]. To minimize the risk of cracking during concreting, it is necessary to apply special measures [19; 20]. Empirical mathematical models for calculating the strength set of concrete and the analysis of temperature fields in concrete structural elements have been developed, the problem of temperature deformations of concrete has been solved [21; 22].

The analysis of scientific and technical information shows that many studies are devoted to the study of the thermal effect on concrete structures. However, many aspects of this problem require further study.

One of the most effective methods of thermal processing of concrete is its infrared heating using gas or electric radiators. Thermal processing using infrared heating for a daily cycle allows you to obtain about 70% of the design strength of concrete. The advantage of this method is the possibility of warming up freshly laid concrete without re-equipping the equipment, since infrared emitters are mobile and can be installed in any convenient place. The disadvantage of infrared heating with gas burners is the need to create an enclosed space in the form of a shelter or tent to protect the gas burners from blowing them out by the wind, which increases the complexity of its implementation. In addition, when heated by infrared radiation, intensive dewatering of concrete from open surfaces is observed, which causes additional shrinkage deformations.

The aim of the study is to improve the technology of construction of monolithic concrete and reinforced concrete structures using infrared radiation, which allows to provide conditions for the normal course of the chemical reaction of hardening and strength gain. To prevent excessive dehydration of the concrete mixture during its thermal processing, it is advisable to use a two-chamber covering transparent to infrared rays.

Experimental program

Materials. The design of the concrete mix was carried out in accordance with the requirements of the Russian standards 27006-86, 7473-2010[1] [23; 24] and taking into account the requirements of ACI 211.1-91[2]. For the preparation of concrete of class C 16/20, the following materials were used: portland cement CemI 42.5*N*, quarry construction sand with a grain size modulus M_{gs} = 2.05, granite crushed stone with a fraction size of 5–10 mm, granite crushed stone with a fraction size of 10–20 mm, water for mixing. The chemical and mineralogical composition of portland cement CemI 42.5*N* is presented in Table 1.

The physical and mechanical properties of portland cement CemI 42.5*N* are shown in Table 2.

The presented materials were used for the preparation of a concrete mixture (Table 3).

Table 1

Chemical and mineralogical composition of portland cement

Chemical composition, %							**Mineralogical composition, %**			
CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	C_3S	C_2S	C_3A	C_4AF
65.94	21.70	5.02	4.20	1.25	0.40	0.78	61.0	16.3	6.2	12.8

Table 2

Physicomechanical properties of portland cement

Indicators	Values
Compressive strength, MPa:	
– at the age of 2 days	22.8
– at the age of 28 days	49.1
Start of setting, min	175
End of setting, min	230
Specific surface, m^2/kg	410

Table 3

Composition of the concrete mix for concrete class C 16/20

Raw material	Weight per 1 m^3
CemI 42.5*N*, kg	420
Sand M_{gs} = 2.05, kg	610
Crushed stone 10–20 mm, kg	730
Crushed stone 5–10 mm, kg	390
Water, L	210
Water-cement ratio	0.5

A heat-resistant film based on polyethylene (polyethylene terephthalate) was used to create conditions for preventing moisture loss by concrete during strength gain. According to the passport data of the manufacturer, the installed heat-resistant film has the following optical characteristics: transparency for infrared rays – 0.86; reflection coefficient – 0.07; absorption coefficient – 0.07.

Experimental procedure. The experimental and theoretical method was used in the study. The preparation of concrete mixtures is carried out according to the recipes presented in Table 3. The preparation of concrete mixes is carried out in a gravity mixer. Mixing of the materials was carried out until a homogeneous mixture was obtained. Cubic samples with a size of 70×70×70 mm were made from the resulting mixture in accordance with the requirements of EN 12390-2:2009[3]. The number of samples produced in accordance with Table 3 is 27 units. Concrete class C 16/20.

The samples are laid in three layers in a styrofoam box with a wall thickness of 50 mm. Chromel-copel thermocouples are installed between the samples. On the open surface of the box, a two-chamber covering is

[1] State Standard of Russia 27006–2019. *Concretes. Rules for mix proportioning*. Moscow: Standardinform Publ.; 2019. (In Russ.); State Standard of Russia 7473–2010. *Fresh concrete. Specifications*. Moscow: Standardinform Publ.; 2018.

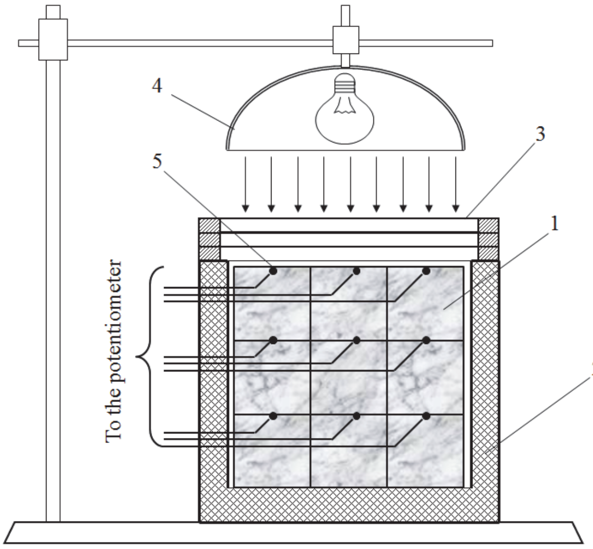
[2] ACI 211.1-91. *Standard practice for selecting proportions for normal, heavyweight, and mass concrete*. Michigan: American Concrete Institute; 1991. (Reapproved 2002.); Svintsov A.P., Svintsova N.K., Nikolenko Yu.V., Gladchenko L.K. *The device for thermal treatment of concrete mix in monolithic designs.* Patent RU 113287 U1. Byul. No. 4. 2012. (In Russ.) Available from: https://www.elibrary.ru/item.asp?id=38400227 (accessed: 00.00.0000).

[3] EN 12390-2:2009. *Testing hardened concrete. Part 2. Making and curing specimens for strength tests*. NEQ. 2009.

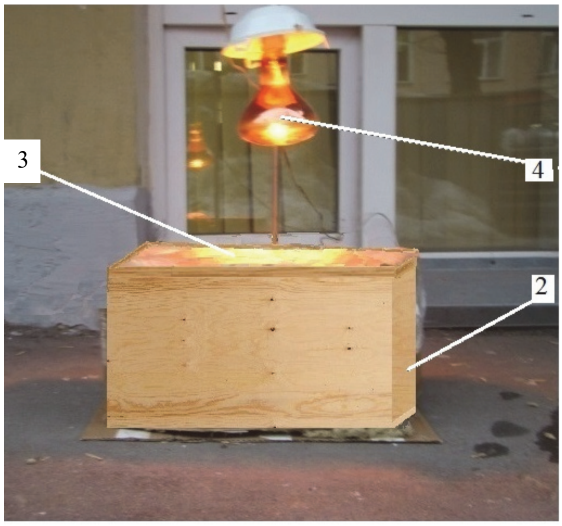
installed, made of a heat-resistant film stretched on frames with a thickness of 15 mm, which made it possible to obtain air chambers of the appropriate size.

Reflector lamp of 500 W was used as the infrared emitters. The amount of heat supplied to the heated concrete was determined and regulated according to known methods. The samples are heated under the condition that the temperature of the concrete on the surface without formwork does not exceed 70 °C.

The experimental verification of the efficiency of infrared heating of concrete using a two-chamber shelter made of heat-resistant film was carried out in natural conditions with cloudy weather, an outdoor temperature of 8 °C and a wind speed of 7–8 m/s. The research methodology provides for the experimental determination of the concrete temperature and its thickness gradient. The layout and shape of the experimental setup are shown in Figure 1.



a



b

Figure 1. Experimental installation for infrared heating of concrete:
a – scheme of the experiment; *b* – installation photo; *1* – concrete sample; *2* – heat-insulated box;
3 – two-chamber translucent covering; *4* – infrared radiator; *5* – thermocouples

In accordance with the experimental plan, temperature measurements were performed in concrete samples with a recording on the coordinate tape of a recording device. The distance from the concrete surface to the infrared radiators was determined experimentally, at which the temperature on the concrete surface under the translucent covering was maintained at 70 ± 2 °C. The heating of the irradiated concrete surface located under a two-chamber covering transparent to infrared rays is on average 12.7 °C/hour, with a standard deviation of 2 °C/hour with a confidence interval of ±1 °C/hour with a security of $\alpha = 0.05$. During the period of isothermal holding of the samples, the temperature of the irradiated concrete surface was maintained in the range from 68 to 71 °C with an average value of 70 °C. The temperature gradient along the concrete cross-section varies from 1.2 to 0.9 °C/cm per hour with decreasing in the direction from the irradiated surface. The cooling rate of concrete after switching off the infrared radiator is from 1.4 to 3.7 °C/hour with an average value of 2.4 °C/hour, the standard deviation is ±0.9 °C/hour and the confidence interval is ±0.5 °C/hour with security $\alpha = 0.05$.

Results and their discussion

The creation of appropriate modes that promote the hydration of cement during concreting include temperature control and moisture exchange. The main purpose of concrete care is to preserve, as far as possible, the saturation of concrete with moisture. Intensive evaporation of water leads to dehydration of concrete, plastic shrinkage and the formation of cracks. The gradual accumulation of cracks of various sizes and directions leads to destructive phenomena of load-bearing concrete and reinforced concrete structures and, ultimately, to their destruction. The effect of an open surface on the relative strength of concrete without taking care of it in the early stages is calculated by empirical dependence [24]:

$$R_{\text{rel.s}} = 92.15 + 166.67\,(C_{\text{rel.c}} - R_{\text{d.s}}), \qquad (1)$$

where $R_{\text{rel.s}}$ is the relative strength of concrete (% of R_{28}); C_c is the relative content of cement in the concrete mixture in fractions of a unit ($C_c = C / (S + Cr + W)$); C, S, Cr, W – components of the concrete mixture (cement, sand, crushed stone, water); $R_{\text{d.s}}$ is decreasing of the relative strength of concrete (%) depending on the modulus of the open surface; M_{os} is the surface module in m^{-1}, $R_{d.s} = -1M_{os}$.

The analysis of the empirical dependence shows that the change in the relative strength of concrete that does not have maintenance in the first few days is directly proportional to the relative content of cement in the concrete mixture and decreasing in proportion to the increase in the modulus of the open surface of the structure. The higher the relative content of cement in the mixture, the higher the strength of the concrete. The strength of concrete decreasing by an amount directly proportional to the modulus of the open surface. The amount of water that the concrete mixture loses, and then the concrete, depends on the temperature and relative humidity of the air, as well as on the wind speed near the open surface of the concreted structure. In addition, the amount of water evaporated from the concrete depends on the modulus of the open surface of the structure. Diagrams of temperature variations of the studied samples are presented in Figure 2.

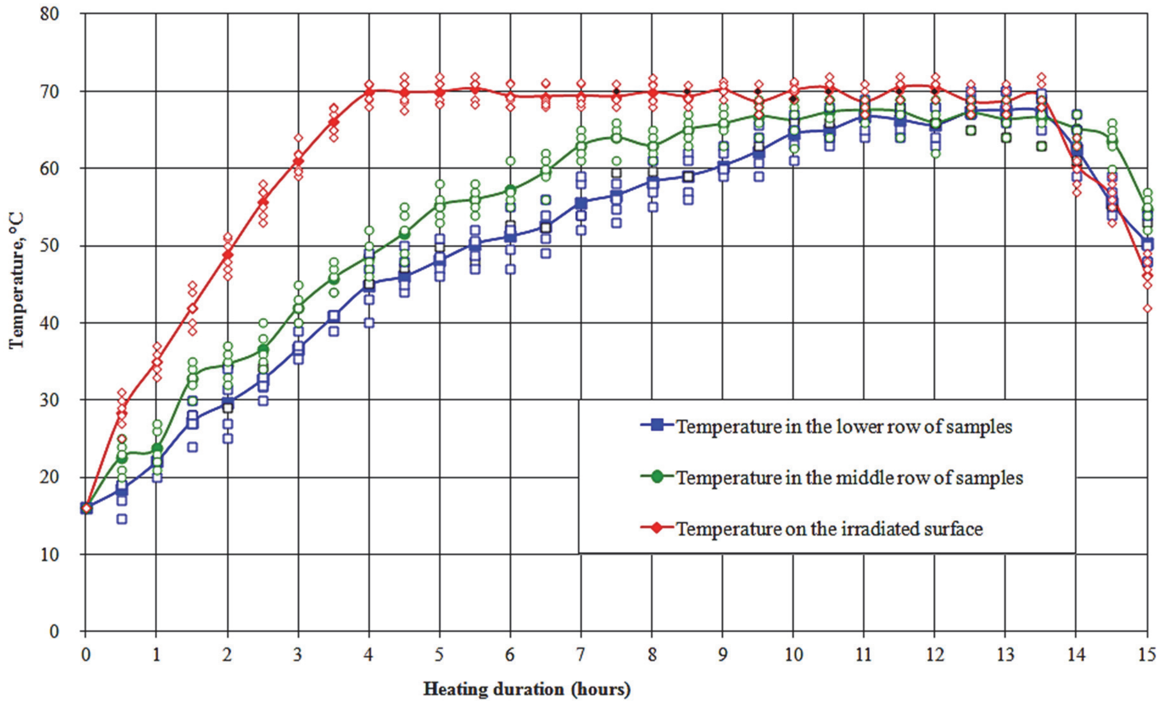


Figure 2. Temperature variation of heated samples

The analysis of the diagram shows that during the period of maintenance of a constant temperature on the irradiated surface, the temperature in the thickness of the samples continues to increase at a rate from 2.6 to 3.1 °C/hour with an average value of 2.9 °C/hour with a confidence interval of ±0.6 °C/hour with a security of α =0.05. Heat preservation on the surface of hardening concrete is an important factor in ensuring normal conditions of hydration of portland cement and preventing the formation of shrinkage cracks. The choice of materials and the design of the covering is of significant technological importance. The main purpose of the covering transparent to infrared rays is to prevent excessive evaporation of moisture from the surface of the hardening concrete.

Concretes subjected to heat treatment under mild curing conditions (60 and 80 °C) gain strength corresponding to the concrete class. This characterizes these conditions as the most favorable for concrete monolithic structures [7]. A higher heating temperature not only accelerates the evaporation of moisture from the concrete, but is also one of the reasons for the lack of concrete strength. Figure 3 shows the changes in the strength of concrete samples for axial compression.

The analysis of the diagrams (Figure 3) shows that with infrared heating, concrete samples gain strength unevenly. The strength set has three characteristic periods. In the first 2–3 hours of thermal processing, the strength set is very insignificant and amounts to 0.1–0.15% of the design value of R_b. Heating of the samples during the next 4–7 hours causes a significant increase in the strength of concrete with an average intensity of 15% per hour. During this period, concrete gains 50–60% of the design value of R_b. Further thermal processing is characterized by a slight increase in the strength of concrete samples with an intensity of 0.5–0.9% per hour. Other researchers have obtained similar results in the thermal processing of hardening concrete in solar cells [23; 24]. The strength set for the depth of its heating varies by 0.3–0.6% per 1 cm of concrete thickness. The relative strength of concrete after heating for 15 hours was 60% R_{28}. The temperature rise in the concrete sample was equal to 4 hours, isothermal holding – 9.5 hours, cooling – 1.5 hours. Thus, the concrete sample gained strength above the critical one.

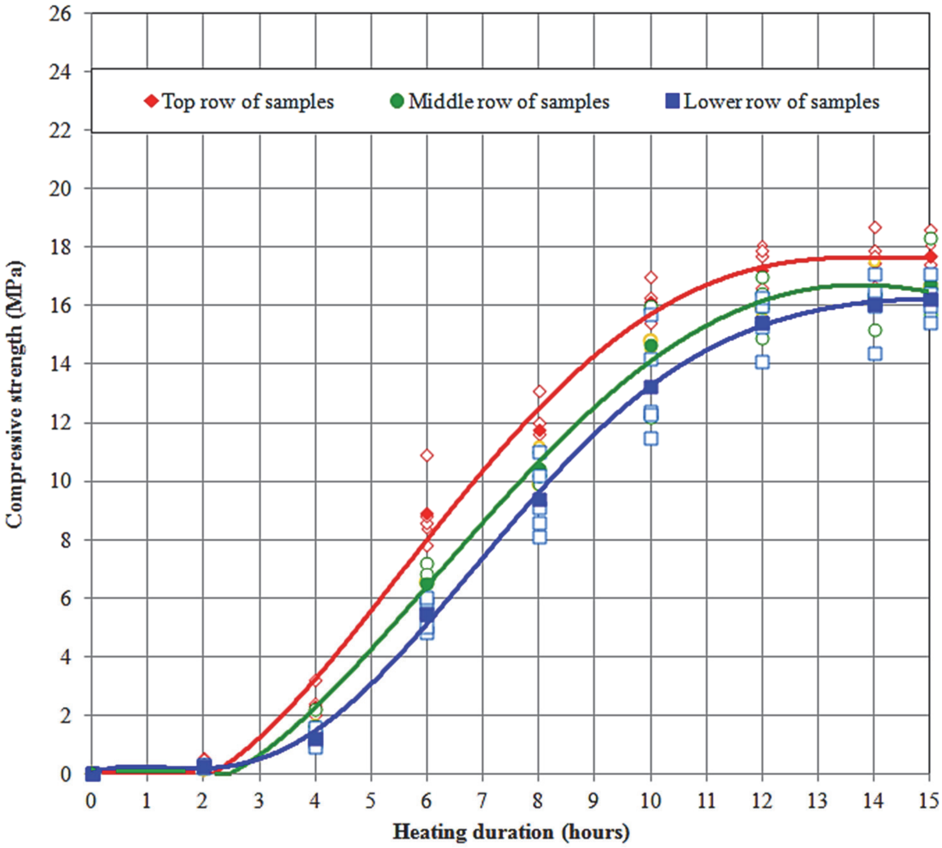


Figure 3. Change in the strength of concrete samples for axial compression

Control samples without thermal processing using infrared radiation were placed in a normal hardening chamber for 28 days. As result of testing of control samples, it was found that the axial compression strength of the samples at the age of 28 days is on average 26.3 MPa.

Calculations show that the estimated electricity consumption for heating 1 m^3 of concrete using infrared radiators and a two-chamber covering is 65–110 kW/hour, which is 15–20% lower than the data available in the literature sources of scientific and technical information. The results of the study are similar to the data [24] obtained when heating concrete with solar energy using a coating of two layers of polyvinyl chloride film stretched on an inventory frame. At the same time, it is noted that the structure of concretes that hardened under conditions of solar heating through a two-layer transparent covering is close to the structure of concretes that hardened under normal conditions. It is important to note that, unlike solar heating, the use of infrared radiators is possible in any cloudy conditions.

The technical solution for heating concrete using infrared radiation is protected by a patent of the Russian Federation[4].

[4] Svintsov A.P., Svintsova N.K., Nikolenko Yu.V., Gladchenko L.K. The device for thermal treatment of concrete mix in monolithic designs. Patent RU 113287 U1. Byul. No. 4. 2012. (In Russ.) Available from: https://www.elibrary.ru/item.asp?id=38400227 (accessed: 00.00.0000).

As noted, one of the features of the technology of concreting with infrared heating is the need to create conditions to prevent the loss of moisture by concrete when gaining strength from an open surface, which causes intense dehydration and cooling. Several layers of material transparent to infrared rays make it possible to create a closed air chamber between the layers and reduce the influence of outdoor air (wind) on the temperature of the laid concrete mixture. The closed air space between the layers of the material serves as a heat insulator from the outside air, and the closed air space located at the surface of the concrete mixture restrains the outflow of heat and water vapor from it into the atmosphere. For practical purposes, it is most advisable to use at least two air chambers (with three layers of transparent material). At the same time, effective heating of the entire surface of the concrete mixture in a structure with heat transfer along its thickness is provided.

An experimental study of the developed technology for heating concrete using infrared radiation and a two-chamber covering has shown its effectiveness in the construction of monolithic concrete and reinforced concrete structures.

Conclusion

To ensure the necessary temperature conditions for hardening and strength gain of concrete, various methods of heating structures are used. The most effective way to heating the open surface of concrete is the use of infrared radiation. Based on the presented results, we can draw the following conclusions:

1. To prevent excessive dehydration of the concrete mixture during its thermal processing, it is advisable to use a two-chamber covering transparent to infrared rays. At the same time, effective heating of the entire surface of the concrete mixture in a structure with heat transfer along its thickness is provided.
2. To prevent the formation of cracks, the maximum curing temperature should not exceed 70 °C.
3. To create conditions to prevent the loss of moisture by concrete when gaining strength, a heat-resistant film stretched on a frame with a thickness of 15 mm was used.
4. The relative strength of concrete after heating for 15 hours was 60% R_{28}, which characterizes these conditions as the most favorable for concrete monolithic structures.
5. A technical solution for heating concrete using infrared radiation has been developed, which allows providing conditions for the normal course of the chemical reaction of hardening and strength gain.

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